Losses Suffered by Coherent Light Redirected and Refocused Many Times in an Enclosed Medium

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If a beam of light is to be transmitted for any considerable distance along the surface of the earth, it will have to be redirected at intervals in order to follow the terrain and focused repeatedly to counteract diffraction. The directing and focusing elements, whether lenses or mirrors, will introduce some loss in addition to that produced by the transmission medium itself. The experiment described in this paper was performed to determine the magnitude of the total loss encountered with such transmission and to determine how much of this loss is due to each of the contributing factors.

A beam of light, enclosed in a metal pipe, was redirected many times by confocally-spaced spherical mirrors, and the loss as a function of the distance over which the beam had been transmitted was determined. At the operating wavelength of 6328 Å these losses, which were found to be almost entirely due to mirror deficiencies, amounted to about 1 per cent per reflection. As a result of the loss being largely in the mirrors the loss per mile depends to a considerable extent upon the spacing between these optical elements. The expected loss for a number of assumed spacings is tabulated.

The experimental results encourage the belief that beams of coherent light can be redirected and focused many times without excessive loss, and that the mechanical stability required can be obtained — in the laboratory at least.

I. PURPOSE OF EXPERIMENT

The advent of the optical maser as a source of coherent light has stimulated considerable interest in the possibility of employing light beams as extremely broadband carriers of information. If a beam of light is to be transmitted along the surface of the earth it will be necessary to redireet and focus it at intervals by means of lenses or mirrors in order to follow the terrain. By employing a sufficient number of redirectors a long-distance transmission system can be built up. A number of such

systems have been proposed by Kompfner.[1] Goubau and Christian have also described such a transmission system.[2] The experiment described in this paper was performed to determine the amount of loss suffered by a beam of light due to transmission through one such system. The experiment has also provided an indication of some of the other problems involved in light transmission, such as that of obtaining the necessary alignment, stability, freedom from vibration, etc.

II. DESCRIPTION OF THE EXPERIMENT

Since the loss through a light-transmission system can be very low, it is desirable when measuring loss to employ a long path in order to obtain accurate measurements. One means of obtaining a long transmission path in a limited space is to use a single path repeatedly, thus making the effective path length many times the actual length. Since mirrors are ideal for folding a transmission path back upon itself, they were chosen as the redirecting elements for this experiment. They have the additional advantages of being simple and available; if spherical mirrors are employed, they can be made to refocus the beam at each reflection.

To isolate the transmission medium from the surrounding environment, it was enclosed in an aluminum pipe 6 inches in diameter. Isolation was the only purpose served by the pipe — it played no part in the actual transmission. Also, since the maximum beam diameter was less than $\frac{1}{2}$ inch, a much smaller pipe would have been satisfactory. Fig. 1 shows the experimental setup in schematic form. The pipeline, which was approximately 330 feet long, was light-tight and was treated

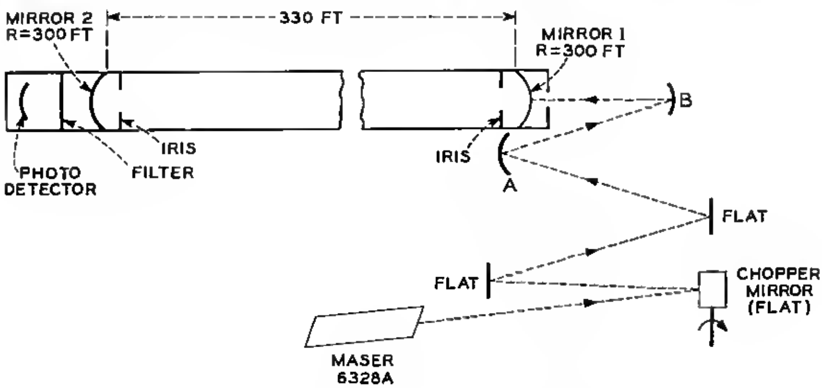


Fig. 1 — Light propagation experiment, system arrangement.

on the inside to minimize reflections. Each end was provided with a spherical mirror with a radius of curvature of approximately 300 feet. This radius was chosen in order to make the configuration nearly, but not exactly, confocal. Each mirror was provided witb an iris which made it possible to adjust its effective diameter from practically zero up to 1.63 inches. The mirrors were coated with dielectric layers to produce a reflectivity of about 99.5 per cent at the operating wavelength of 6328 angstroms.

The mirrors 1 and 2 arranged in the configuration shown on Fig. 1 constitute a confocal resonator as described by Boyd and Gordon[3] and by Fox and Li.[4] Some consideration was given to the idea of applying light to the line continuously and determining losses by tbe usual method of measuring the "Q" of the resonator. However, because of the extremely high Q, the requirements imposed on mechanical stability would have been formidable, so a more feasible method was sought. The stability requirements were reduced to reasonable values by applying light to the line in short pulses. The pulse duration was made less than the round-trip transit time through the line so that there would be no overlapping of pulses and hence no critical relationship between the light wavelength and the mirror spacing.

With this configuration, when a pulse of light strikes a mirror some of it is lost but most is refocused and reflected to the opposite mirror. Here it is refocused and reflected back to the first mirror and so on indefinitely. In this way each single pulse of light applied to the line results in a train of pulses decaying in intensity, with the rate of decay providing a measure of the transmission losses.

Part of the light lost at each reflection was transmitted through the dielectric coating of the mirror. The part transmitted through the mirror at the far end of the line was applied to a photomultiplier, the output of which was, in turn, applied to an oscilloscope or other measuring equipment. We thus obtained an output from the line witbout increasing the losses, since this light would have been dissipated in any case. Since most of the light striking a mirror was reflected, and some of the remainder absorbed, the loss from the line into the measuring equipment was high, being about 26 db for the mirrors employed. For the same reason we were able to get light into the line without increasing losses by going in through the back of the mirror at the near end. Here, again, the loss was about 26 db.

The light-signal source was a dc-excited helium-neon gas maser about one meter long, of the type described by White and Rigden.[5] One of the maser mirrors was stopped down with an iris to sucb an extent that

it could oscillate at only the fundamental transverse mode. The several longitudinal modes present caused no difficulty since there were no frequency sensitive elements involved. The output power was approximately 1 milliwatt.

The output beam was chopped into short pulses by means of a small, flat, rotating mirror which could be driven at rates up to 40,000 rpm (see Fig. 1). Pulses as short as 0.2 microsecond could be obtained, because the beam was effective in exciting the line only during the very short time that it was accurately aligned with the axis of the pipe. Since the round-trip transit time for the line was nearly 0.7 μsec, pulses of 0.5 μsec duration were sufficiently short, and the chopper could be run at considerably less than its maximum speed. The mirrors A and B shown in Fig. 1 between the chopper mirror and the end of the line served the purpose of focusing the beam to get it launched properly, as discussed in the next section. Sweeping a light beam across the mirrors of a system such as this undoubtedly produces many higher-order modes. However, these modes are generated when the beam is out of alignment with the axis of the line, are off-axis modes, and die out very rapidly.

III. BEAM LAUNCHING

Refs. 3 and 4 show that after many reflections in a confocal system the light has a very definite distribution of intensity at each part of the resonator. Further, this distribution is the one which provides the lowest losses. If light is launched into the line with this distribution, losses and starting transient effects will be minimized. Using equations (19) and (24) of Boyd and Gordon[3] we calculate a beam diameter of 0.35 inch at each end mirror and 0.25 inch at the center of the line. If the beam is launched into the line in such a way as to fit these dimensions there will be a minimum of loss. Launching conditions were controlled by two spherical mirrors, A and B, shown in Fig. 1 mounted between the chopper mirror and the end of the line. These mirrors were spaced so as to be nearly confocal, with the second mirror having twice the focal length of the first in order to provide a two-to-one increase in beam diameter. To minimize the distortion of beam shape produced by the spherical mirrors the launching arrangement was set up to provide as nearly as possible normal incidence on these mirrors. By proper adjustment of the spacing between the focusing mirrors the beam was made slightly convergent as it entered the line. It converged to the center of the line, where it reached a minimum diameter and then diverged slowly until it reached the mirror at the far end of the line. Here it was reflected and again made converging, thus repeating the process.

The beam was photographed at various points in the line in order to determine its cross section. Some of the photographs, which were taken with the beam not being chopped, are shown in Fig. 2. Fig. 2(a) shows the beam as it entered the line. It was 0.37 inch in diameter in comparison to the calculated value of 0.35 inch. The ring segments directly above the spot were part of an interference pattern produced by reflections from the back surface of the output mirror of the maser. Fortunately the reflected light left the maser at an angle slightly different from that of the transmitted beam, and as a result the two beams were fairly well separated in space at the center of the pipe line. This is seen in Fig. 2(b), which shows the beam diameter to have decreased to 0.28 inch at this point. Fig. 2(c) shows that by the time the beam reached the far end of the line its diameter had increased to 0.4 inch. Figs. 2(d), (e) and (f) show the beam after it had been reflected the first time from the mirror at the far end of the line. The focusing effect of this mirror is quite evident. Although the measured beam diameters are somewhat different

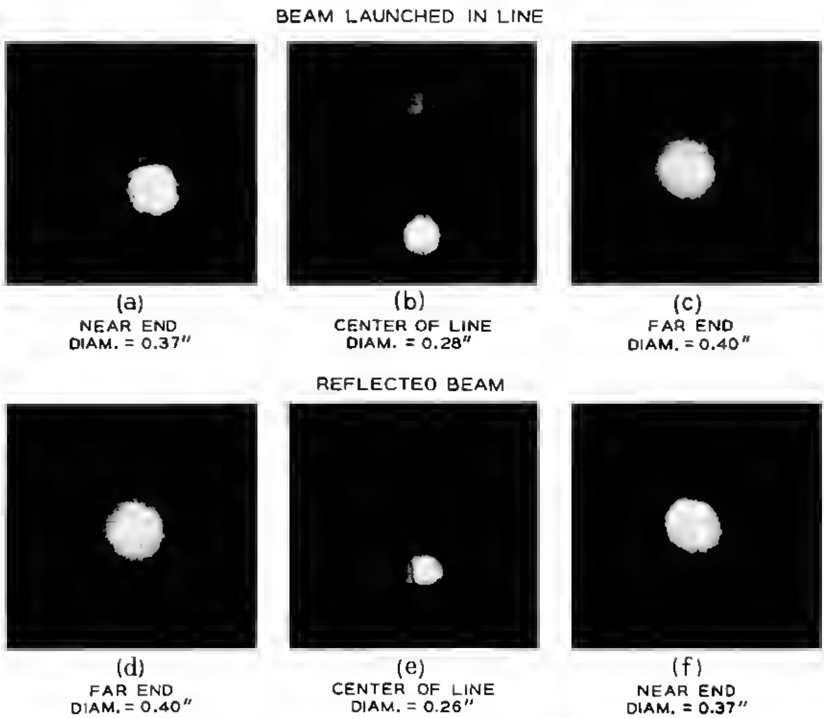


Fig. 2 — Beam cross sections.

from the calculated values, they differ by only about 12 per cent in the worst case.

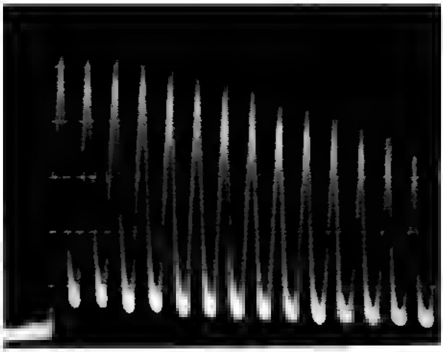
IV. DETERMINATION OF LOSSES

4.1 *Two-Mirror Shuttle-Pulse*

Fig. 3 illustrates the performance of a shuttle-pulse experiment described above and shown in Fig. 1. For this figure, which illustrates the decay of light power with successive reflections, each pulse on the oscilloscope trace represents one round trip of the light beam through the transmission line, there being a total of 75 pulses shown. For Fig. 4 the oscilloscope sweep was expanded to show individual pulses. Fig. 4(a) shows the first 13 round trips. Fig. 4(b) shows pulses corresponding to 300 to 310 round trips for a distance of 37.5 to 39 miles. Pulses which have made 400 round trips for a total distance of 50 miles have been detected with little difficulty. The first pulse in the group shown on Fig. 4(a) is the one applied to the line. It has a peak power of only 5×10^{-9} watts when it arrives at the cathode of the photomultiplier tube.

Fig. 5 is a typical plot of power loss versus number of trips through the line. After about 40 trips the loss is seen to remain constant at the rate of 0.046 db per trip, which corresponds to a power loss of 1 per cent per trip. The fact that the loss was somewhat higher for the early trips may be due to higher-order modes, present because of imperfect launch-

Fig. 3 — First 75 round trips; illustrates decay of light energy produced by successive reflections.



(a)

(b)

Fig. 4 — Individual pulses: (a) first 13 round trips, (b) round trips number 300 to 310.

ing of the beam. These results were obtained with effective mirror diameters of 0.87 inch, which corresponds to a Fresnel number N of 2, where N is equal to $a^2/b\lambda$; a is the mirror radius and b the spacing between mirrors.

In order to determine the effects of diffraction on the measured losses the value of N for the system was varied, in steps, from 0.5 to 4 by adjusting the iris in front of each mirror, thus changing the effective mirror diameter. The photographs of Fig. 6 illustrate the effect of N upon losses. It is interesting to compare Fig. 6(e), for small mirrors at both ends, with Fig. 6(f), where the diameter of the mirror at the receiving end has been increased. When making comparisons involving an arrangement of mirrors with different diameters the losses should be considered

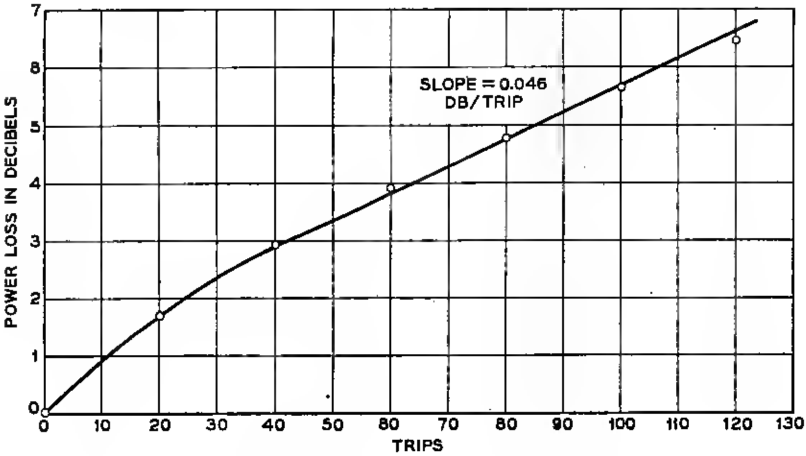


Fig. 5 — Power loss versus number of trips through the line.

on a round-trip basis so as to include one reflection from each mirror. For the case shown by Fig. 6(e) the loss was 14.5 per cent at each mirror. For the conditions of Fig. 6(f) one might expect the losses to be 14.5 per cent for the small mirror and 1.5 per cent for the larger mirror, to give a total round-trip loss of 16 per cent. Fig. 6(f) shows this loss to be only 6 per cent. The lower loss resulted from the fact that the light redistributed itself to matcb the changed configuration, there being a smaller beam diameter at the small mirror and a larger beam diameter at the large mirror.

Fig. 7 shows a plot of measured loss versus N and also diffraction loss as calculated by Fox and Li plotted against this same parameter. It is evident that for values of N of 0.6 or less diffraction losses predominate, whereas for values of N greater than 1.0 other losses are more important. The curve labeled "expected loss" was obtained by adding the known mirror loss of 0.5 per cent to the calculated diffraction loss.

It can be seen that in the region of high losses the measured losses are close to the diffraction losses as calculated by Fox and Li. The data of Fig. 7 are somewhat inaccurate for two reasons. For the lower values of N the mirror diameters were small and it was much more difficult to obtain accurate system alignment, so that there are possibly some alignment losses included. Also, the losses become so high for low values of N tbat we have only a few trips througb tbe line before the signal becomes comparable to the noise. As a result losses must be measured in a region wbere higher-order modes are important. More accurate results could be

obtained if cnougb power wcre available to make it possible to determine the rate of decay after 50 tó 100 trips where tbe higher-order modes have had time to die out. The presence of higher-order modes probably accounts for the fact that losses are still decreasing witb increase of N for values of N as great as 4.

4.2 *Periscope System*

If mirrors are to be used as beam directors in a practical system they will need to be used in pairs. Kompfner[1] bas suggested pairs of cylindrical mirrors; however, a plane mirror to direct the beam in combination with a spherical mirror for focusing also appears to be a satisfactory arrangement. A transmission path made up of such pairs is shown schematically in Fig. 8(a). It is evident that this combination allows the direction of the beam to be changed at any pair of mirrors.

In order to simulate the use of mirror pairs, two plane mirrors were inserted near the center of the transmission path as shown in Fig. 8(b). Except for the addition of the two plane mirrors the system was operated

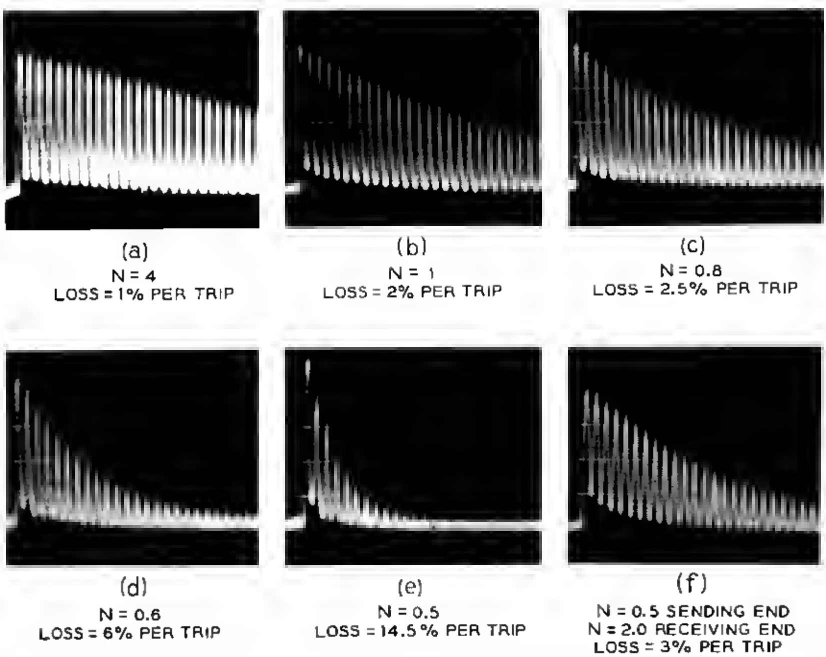


Fig. 6 — The effect of mirror diameter on loss.

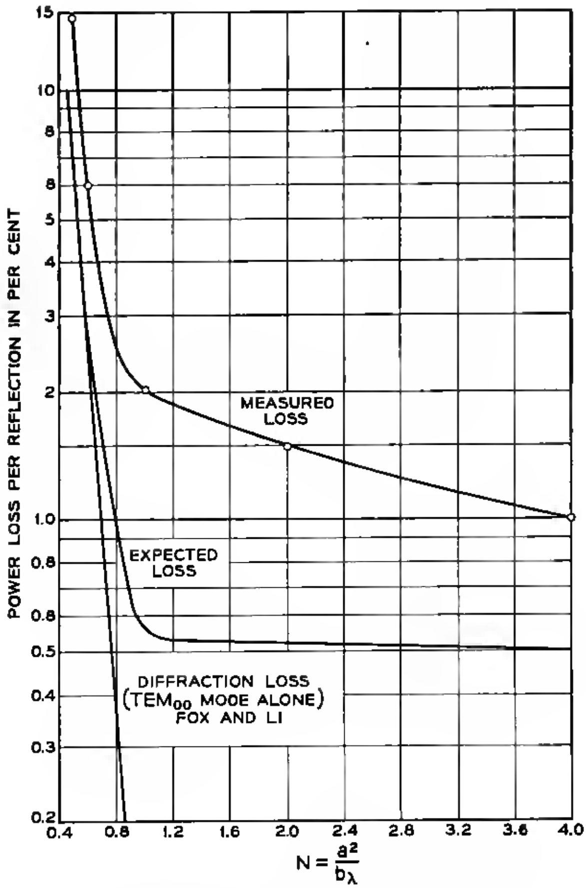


Fig. 7 — Comparison of measured loss with expected loss.

just as before, with pulses of light shuttled back and forth between the two spherical mirrors at the ends of the line. With this configuration there were three reflections per trip in comparison to one reflection for the two-mirror case. For tbis arrangement the total loss was measured to be 0.08 db, or 2 per cent per trip in comparison to 1 per cent for the two-mirror system. The loss was thus increased by 0.5 per cent per reflection from tbe flat mirrors, which is just the reflection loss of these mirrors.

4.3 *Multimirror Experiment*

The two-mirror shuttle pulse experiment differs from a practical transmission line in one other respect — the same two mirrors are used re-

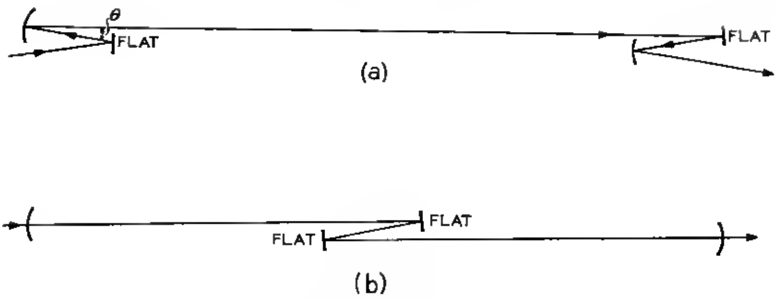


Fig. 8 — (a) Use of mirror pairs to change beam direction; (b) experimental equivalent with flat mirrors at the center of the line.

peatedly, whereas in an actual system each reflection would involve a different mirror.

In order to obtain a better simulation of an actual line a multimirror experiment was planned. Mirrors were purchased for this experiment but, unfortunately, upon delivery were found to be defective. The best we could do was to set up a four-mirror experiment with the four good mirrors available. These mirrors, which were of excellent quality, were ground by the Schutte Optical Company, Incorporated of Rochester, New York, and coated by W. L. Bond of the Murray Hill, N. J., Bell Laboratories. The mirrors were first set up in a four-mirror shuttle pulse experiment as indicated in Fig. 9(a). For this arrangement the light traversed the path M_1, M_2, M_3, M_4, M_3, M_2, M_1, M_2, etc. The same four mirrors were also arranged in a circulating loop as shown in Fig. 9(b). Here the light path was M_1, M_2, M_3, M_4, M_1, M_2, etc.

Fig. 10 is a plot of the losses measured for the four-mirror shuttle

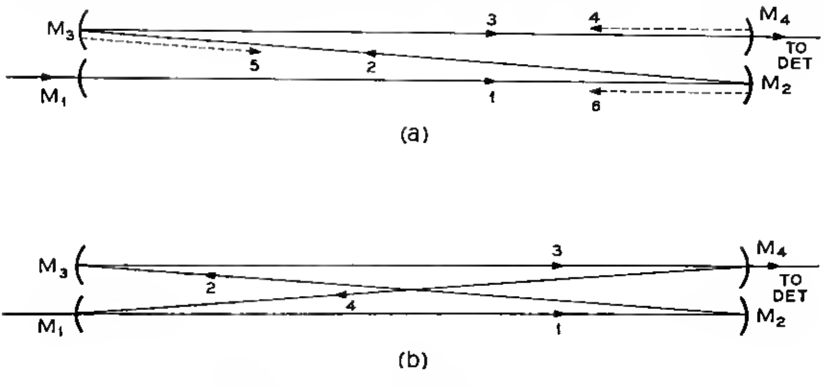


Fig. 9 — Some four-mirror experiments.

pulse, the four-mirror circulating loop and a two-mirror shuttle-pulse system. After it has reached a steady value the loss is seen to be the same, 0.05 db per trip, for all three systems.* A number of comparisons have yielded no measurable difference between the losses for a two-mirror system and a four-mirror experiment. This tends to indicate that the shuttle-pulse data can be applied to a long, straight-through system. Obviously more conclusive results could be obtained from an arrangement using at least ten mirrors, set up either as a circulating loop or as a shuttle-pulse experiment.

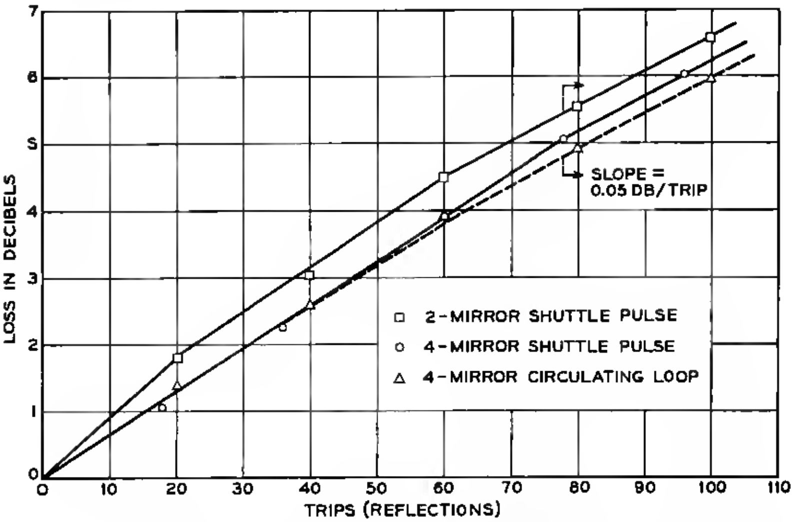


Fig. 10 — Comparison of four-mirror system losses with two-mirror system losses.

V. LOSSES

According to the best data available from other measurements our mirrors have reflectivity of 99.5 per cent or a reflection loss of 0.5 per cent. The measurements described here yield a loss of 1 per cent per trip through the line when there is one reflection per trip. This leaves a 0.5 per cent loss per trip to be accounted for. We know, both from theory and experiment, that for an N of 2 diffraction loss is negligible. The remaining half per cent of loss, amounting to 0.023 db per trip, must have

* This is slightly greater than the 0.046 db per trip for the two-mirror shuttle pulse as plotted in Fig. 5. The two sets of data were taken at different times, which could well account for the discrepancy.

been due to the atmosphere contained in the pipe, to lack of perfect mirror alignment and to beam spreading and scattering produced by mirror imperfections, dust particles etc. All of these except atmospheric losses should decrease with increasing mirror diameter. The plot of measured loss of Fig. 7 shows this loss to decrease with increasing mirror diameter for values of N up to 4 or more. This would indicate that at least part of the loss is due to misalignment and the beam spreading which results from the presence of higher-order modes.

In general, atmospheric losses result from absorption by water vapor, carbon dioxide and oxygen, and from scattering by small particles of dust etc. The losses measured for the 330-foot line are slightly smaller than those determined by the author from a similar shuttle-pulse experiment in which the mirrors were only 110 feet apart. Any atmospheric losses should, of course, be greater for the longer line. This indicates that small, undetermined differences in mirror loss* were more important than the atmospheric loss and that the latter is too small to measure accurately by this experiment. From a study of data on the solar spectrum after transmission through the Earth's atmosphere, Long and Lewis[6] conclude that atmospheric absorption losses should be negligible at our operating wavelength of 6328 angstroms.

At first thought the conclusions stated above might be considered inconsistent with experimental data obtained by Taylor and Yates.[7] For a path over water they measured a loss of 1.1 db per mile for a 3.4-mile path and 0.63 db per mile for a 10.1-mile path at our operating wavelength. Even the smaller of these losses is considerably greater than the 0.37 db per mile which we are attempting to account for. The results obtained by Taylor and Yates probably do not apply to our setup for several reasons. In the first place, part of the losses they measured may have been due to haze, water droplets, dust, etc. which we do not have in the pipe line. Also, for their experiment, each determination of loss was made over a band of wavelengths, whereas for the experiment described here we are dealing with monochromatic light. Burch, Howard and Williams[8] have pointed out that results measured for the wideband case do not necessarily apply to the transmission of monochromatic light.

Taking all of the above factors into consideration we are led to the conclusion that atmospheric loss in the pipe is much less than the 0.37 db per mile which is unaccounted for.

Of particular interest to a system designer is the loss per mile which can be expected. For a light-transmission system where the beam is re-

* The mirrors employed in the two experiments were supposed to be identical except for radius of curvature.

directed at intervals this loss will depend to a great extent upon the spacing between directors. For the 330-foot spacing and using the periscope arrangement we have measured 0.08 db per trip for mirrors of 0.875-inch diameter. This corresponds to 1.28 db per mile. This figure is pessimistic, since three reflections per trip were involved in the experiment, whereas in an actual line involving pairs of mirrors there would be only two reflections per link. This should reduce the loss to 0.96 db per mile.

From the experimental data it is possible to determine what the approximate value of loss would be for various spacings between directors. Some of these values are listed in Table I along with the assumed conditions. This table is based on the assumption that each director consists of two mirrors, each with a reflection loss of 0.5 per cent, and, unless otherwise stated, the loss produced by the atmosphere in the line is assumed to be 0.1 db per mile. An additional 0.5 per cent is added for each mirror pair to represent the loss still unaccounted for.

For all of the cases listed in the table the mirror diameter is great enough to make diffraction losses negligible. Although decreasing the mirror diameter to values somewhat less than those shown in the table would not cause an appreciable increase in loss, such a decrease would make alignment more critical and decrease stability.

VI. PROBLEMS ENCOUNTERED

A number of the problems encountered in this experiment will also be present in any practical system. For this reason some of these will be discussed briefly.

6.1 *Alignment*

If losses are to be kept small it is obviously necessary to obtain rather accurate alignment. Not only must the beam be launched along the axis

Table I — Losses for Various Spacings between Directors

Spacing between Mirror Pairs	N	Mirror Diameter (inches)	Assumed Atmospheric Loss, db/mile	Total Loss, db/mile
165 feet	1.3	0.5	0.1	2.02
165 feet	1.3	0.5	0	1.92
330 feet	2.6	1	0.1	1.06
330 feet	2.6	1	0	0.96
1,320 ft (0.25 mile)	2.6	2	0.1	0.34
1,320 ft (0.25 mile)	2.6	2	0	0.24
2,640 ft (0.5 mile)	1.3	2	0.1	0.22
2,640 ft (0.5 mile)	1.3	2	0	0.12

of the line but each reflection must be such as to keep the beam on this axis. Simple calculations show that, for the 330-foot line, a tilt of 20 seconds of arc of one of the mirrors results in the displacement of the beam by a full beam diameter at the opposite end of the line; greater mirror spacings would be still more critical. In spite of the stringent requirements it has been feasible to obtain satisfactory alignment for the mirror spacings used in this experiment.

6.2 *Stability*

Both the shuttle-pulse experiment and the circulating loop described here are affected to a much greater extent by mirror movement than a carefully designed straight-through system of the same length would be. For the experimental systems, rotation of a mirror through an angle θ would shift the beam, for a single reflection, through an angle 2θ. For a straightaway system employing pairs of mirrors, as shown on Fig. 8, the situation would be quite different. If the two mirrors of a pair are parallel and are mounted close together on a rigid mount, small rotations of the mount will produce no angular deviation of the transmitted beam, since both mirrors rotate together. At those locations where it is desired to change the direction of propagation, the mirrors in a pair will not be parallel and rotation of the mount will result in some angular deviation. However, for small departures from parallelism the combination will still be very superior to a single mirror and deviations will be small.

A system using mirrors in this way is sensitive to rotation of either mirror with respect to the other mirror of a pair. Such relative motion can be minimized by mounting each pair of reflectors on a very rigid mount, made of material with a low coefficient of expansion. A pair could be enclosed in a comparatively small volume, which would make it practical to control the temperature of the complete mount and thus assure additional stability.

The only precautions taken to provide stability in the experimental set-up consisted of employing rugged mirror mounts and isolating the mirrors from mechanical motions of the pipe line. The latter was accomplished by mounting the end mirrors on rigid platforms which were only very loosely attached to the pipe. In spite of these shortcomings of the experimental system, it would operate for hours without readjustment. Only large temperature changes produced serious deflections of the beam. It is evident that the inherently superior stability of a straight-through system would go far toward compensating for its much greater length.

6.3 *Atmospheric Turbulence*

In spite of the fact that our experimental line is inside a building there were point-to-point differences in temperature sufficient to produce air currents inside the line. The resulting variations in index of refraction as masses of air at different temperatures moved through the heam caused random fluctuations of the position and shape of the beam arriving at the end of the line. This difficulty was overcome by applying a one-inch layer of insulation over the line, which reduced fluctuations to tbe point where they were no longer discernihle.

The shuttle-pulse experiment is considerably less susceptible to turbulence effects than a straight-through system of the same length would he. Any movement of air masses will take place in times long in comparison to transit time through the line. Hence any displacement of the beam hy passage through a refractive region will be almost exactly canceled hy passage through the same region, hut in the reverse direction, on the return trip. Conversely, air turhulence has a greater effect on the circulating loop of Fig. 9(h) than on a straightaway system. In the loop the beam passes many times in the same direction through any discontinuity and each time is deflected in the same way whereas, for the straight-through system, there would he only one passage through auy one discontinuity and the resultant deflections would he random. Insulating the line reduced turhulence effects to the point where they were insignificant — even with the circulating loop.

In a practical system air currents could be made negligihle by partial evacuation of the line or possihly reduced to a sufficiently low value hy other means. In any case the heam enclosure would most likely he installed underground, where temperature variations are much smaller than they are out in the open air.

VII. THE LINE AS A RESONANT CAVITY

Some experiments have heen performed with the chopper mirror stopped in such a position that the heam was continuously lined up with the axis of the line. There was evidence of resonance in that the intensity of the beam transmitted through the line increased very noticeahly when the mirrors were properly aligned. This increase was very evident to the eye even though it responds only to average intensity. The photomultiplier output as recorded in Fig. 11(a) shows that, as expected, the line was continuously going in and out of resonance in a very random manner. In this picture the most negative pulses correspond to the greatest light intensity and result when the system is nearest to reso-

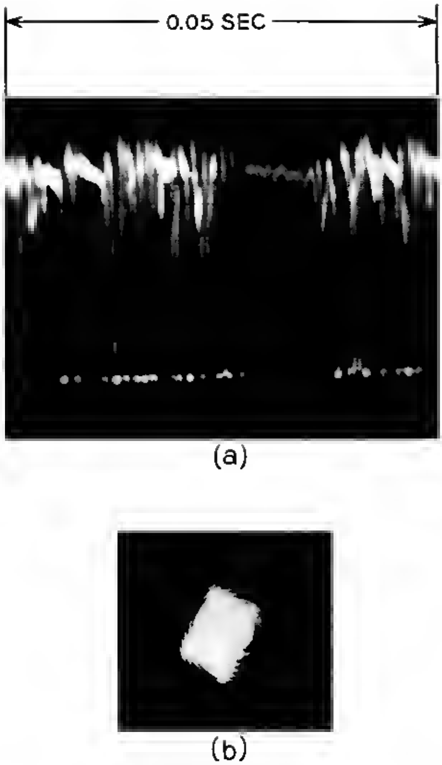


Fig. 11 — Continuous light iuput, line near resonance: (a) photomultiplier output, (b) beam cross section at one mirror. Mirror diameter 1.63 inches.

nance. It is seen that during the 50-millisecond period represented by the picture the system was out of resonance most of tbe time but went into, or through, resonance for short intervals. A very slight tapping of the maser produced a large increase in the number of pulses obtained, probably by causing the frequency to sweep back and forth through the resonant value. The peaks shown do not represent maximum buildup, for two reasons. First, the output amplifier was obviously overloading and, second, the true resonant condition probably never lasted long enough for the intensity to build up to its maximum value. Peak intensities during resonance bave been measured to be as mucb as 100 times the intensity for the nonresonant condition. The calculated value of the Q for this system is 9.9×10^{10} based on a loss of 1 per cent per reflection. It is not surprising that adjustments are very critical.

Fig. 11(b) illustrates the effect of misalignment of the mirrors. The

photograph shows the pattern formed on the mirror at the far end of the line with light applied continuously at the near end and after an attempt had been made to adjust the system to resonance. The rectangular shape of the pattern indicates that there were higher-order modes present. More careful adjustment resulted in a pattern corresponding to only the lowest-order mode, i.e., a beam with a circular cross section, similar to those shown in Fig. 2.

The photograph of Fig. 12 shows an example of exaggerated misalignment. For this case the mirrors were deliberately tilted out of adjustment and the beam was applied off axis. As a result the beam did not double back on itself but followed a different return path, and therefore made a different spot on the mirror for each round trip. The picture

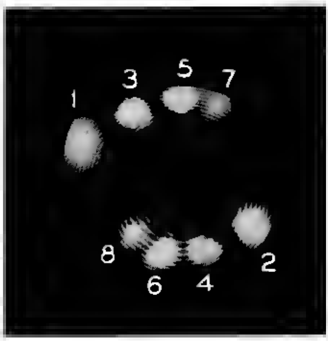


Fig. 12 — Multipath transmission: 1.25-inch diameter tilted confocal mirrors.

shows that there were seven round trips through the line before the beam was finally lost. It should be possible to obtain an adjustment which produces a pattern of the type shown but which is repetitive and continues indefinitely without the beam becoming lost.[9] It is evident that even the degree of misalignment shown on Fig. 12 does not cause excessive loss as long as the beam is confined to the surface of the mirrors, but that the greater the degree of misalignment the larger the mirrors must be to meet this requirement.*

VIII. CONCLUSIONS

Results of the experiment described above show that, under proper conditions in an enclosed path, coherent light can be transmitted with

* Figs. 11 and 12 were obtained from the 110-foot line, which accounts for the small beam diameters. The circular lines running through the beams result from interference between reflections from the back and front surfaces of the mirrors.

low loss even when it is necessary to redirect the beam at relatively short intervals. Since a large part of the transmission loss is in the directors, in this case mirrors, the loss per mile depends upon how close together these directors must be placed. If future development produces better directors, then losses should be even lower than those measured in this experiment. Also, other devices may well prove to be superior to mirrors as beam directors.

In a practical transmission line the spacing between directors will be dictated to a considerable degree by the terrain being traversed. Another very important factor involves the difficulty of keeping the directors properly aligned in the presence of vibration and temperature changes. There is also the problem of air currents in the line.

For the experimental system the vibration problem was solved by ruggedizing all components. Insulation of the pipeline reduced air currents to the point where they produced no measurable effects. Although temperature changes produced displacements of the beam, these deviations were small enough, in the laboratory environment, to be tolerable even though no other steps were taken to provide temperature stability. The question as to whether or not these problems can be solved in a practical transmission line has not been answered by this experiment. The difficulties will be greater in the practical line and will call for more sophisticated design; however, the fact that the problems were solved with relative ease for the experimental set-up is encouraging.

The work described here represent only a fraction of the interesting and informative experiments which could be performed using this technique.

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